Analysis of Thrust of Underwater Vehicle with Undulating Propulsion

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Abstract. This article presents a preliminary study of determining the effect of the control parameters, shape and stiffness of the tail fin and the lateral fins on the thrust of the fifth version of polish biomimetic unmanned vehicle (BUV) called CyberFish. In the second paragraph the BUV's construction and its rule of motion is shortly mentioned. The next paragraph presents results of thrust measurements and conclusions from conducted tests. Conclusion summarizes influence of control parameters, tail fin and lateral fins on the average thrust of the CyberFish.

Keywords: Biomimetic Unamnned Vehicle, BUV, Underwater Mobile Robot, Thrust Force Measurements, Undulating Propulsion, Robotic Fish, CyberFish.

1 Introduction

In the recent years a rapid growth in biomimetic robotic constructions can be noticed. Particular attention is drawn to mobile robots that mimics the behavior of organisms inhabiting water environment. Some biomimetic underwater robots construction is presented in [1]. The fastest growing group of biomimetic underwater vehicles with subcarangiform or carangiform type undulating propulsion which are reflecting salmon or perch family fish. A characteristic feature of these vehicles is to perform the undulating motion using at least half the length of the body. Publication, [2 3] presents details of similar prototypes of BUVs. Some experiments on biomimetic underwater vehicles maximal speed was done by Wai Leung Chan et. all. [4]. The only difference is the type of the robot was ostraciiform which means that the tail consisted of only one segment. Similar experiments but with three-segment subcarangiform type fish was done by authors in [5]. In the available literature there is the lack of thrust analysis for different BUV's and control parameters influence on that thrust. Some research on influence of frequency and amplitude of osculation of robot's drive and type of the tail fin on the robot's thrust was done by C. W. Chong et. all. in [6]. In this paper authors presents results of experimental studies on average thrust of carangiform type biomimetic unmanned vehicle called CyberFish in extend

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range of frequencies and amplitudes of robot's drive. Furthermore the influence of the tail fin and lateral fins on the thrust was examined.

2 The Experiment

2.1 Fifth Version of CyberFish

CyberFish is the biomimetic unmanned vehicle (BUV) which mimics Carp fish both in the external shape and its kinematics [7]. The hull of the robot was designed based on the 3D scan of a real fish in CAD software. All the necessary mechanical parameters (density of material, masses and arrangement of the internal devices etc.) to obtain close to neutral final buoyancy of the vehicle was estimated during the design process. DFM (Design For Manufacturing) and DFA (Design For Assembly) methodology was also taken into account. After the 3D model of the robot was done all the elements of the hull where manufactured from polyethylene (PE500) by means of CNC milling. Some internal parts for equipment integration was made of laser cut and welded stainless steel. Some fin elements was made of 3 mm rubber with the ability to detach them from the hull and replace them with different material. The robot's mechanical structure contains the payload segment (the head) in which the control board, communication modules and sensors are installed. Additionally in this section the variable buoyancy system (artificial swim bladder), the lateral fins servomotor and the first segment of the tail servomotor are placed. Tail section of the vehicle contains three segments connected with each other with class V rotary kinematic pairs. The first and the second segment of the tail also contains servomotors for their drive as well as additional batteries. The third segment of the tail is solid block of polyethylene with slot for mounting tail fin. Each servomotor of the vehicle (4 in total) is connected to RS-485 bus and enables for precise position and speed control. Drives overload and overheating can be detected. Variable buoyancy system is driven by separate BLDC motor. The CyberFish is powered with three packets of 11.1 V Lithium-Polymer batteries with total capacity of 2400 mAh which enables the robot to operate for three hours (dependent on the control parameters). Batteries can be recharged without removing them from the hull, using terminals located on top of the first segment of the tail. During robots operation terminals are disconnected from the batteries by means of magnetic switches. The CyberFish is also equipped with MEMS based inertial measurement unit (3-axis accelerometer, 3-axis gyro, 3-axis magnetometer) which was used for research on robot's control parameters influence on its tilt, heel and sway. The results of these work are the subject of different paper [8]. The robot is manually controlled but future work is concerned with development of robots partial autonomy Figure 1 presents the view of the CyberFish during free swimming in the pool.

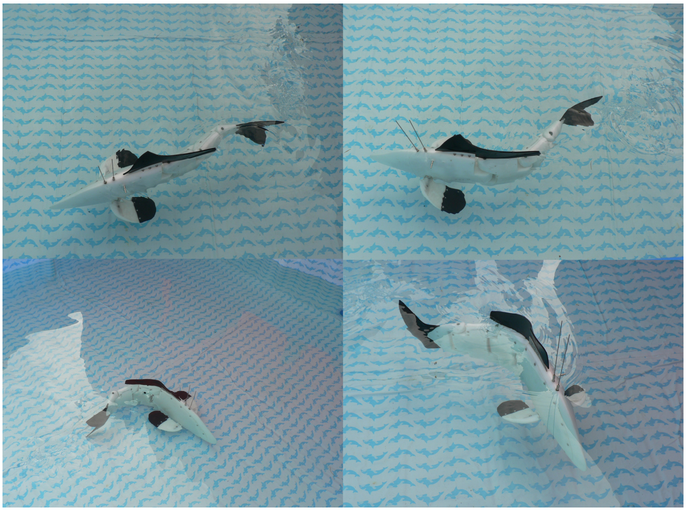

Fig. 1. BUV during free swimming in the pool (own elaboration)

2.2 The Test Stand

In order to measure BUV's thrust the test stand was build (Fig. 2). The test stand contains: the CyberFish (1), the non-malleable links (2), the stainless steel frame (3), the tensometric small force transducer AST KAP-S (4) of maximum load 10 N and resolution of 0.001 N, computer for data acquisition (5) and a water tank (4 m length, 2 m width, 1 m depth). Links where connected to the CyberFish through a pulley in order to eliminate adverse force components. The robot, the links and the lower part of the frame where immersed in water while the upper part of the frame with mounted force transducer extends above water surface.

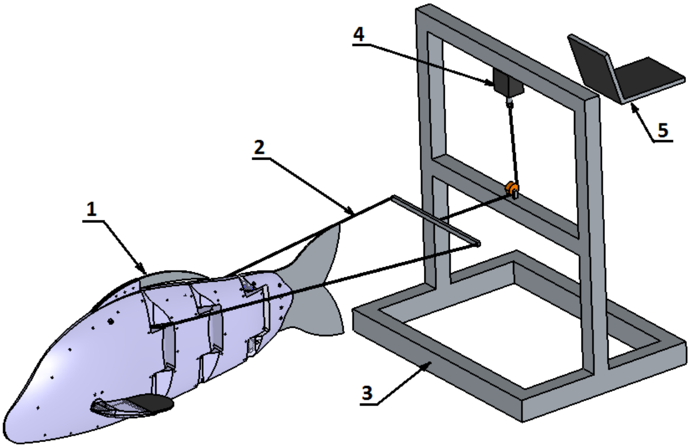

Fig. 2. The scheme of a test stand for vehicle's thrust measurements (own elaboration)

Robot's motion along straight line can be achieved in three ways:

- using variable buoyancy system and lateral fins angle of attack change only;
- using lateral fins oscillations only or with variable buoyancy system for depth control;
- using tail undulations only or with variable buoyancy system and lateral fins angle of attack change for depth control;

There is the possibility to changing the volume of water in variable buoyancy system connected with adjusting angle of attack of lateral fins thus the vehicle will move along using lift force generated on lateral fins by variable buoyancy force. In this case the motion of the fish seems to be the most energetically efficient and desirable in situations when the hull oscillations should be significantly reduced.

CyberFish is able to move by means of oscillations of lateral fins. In this case the robot's thrust depends on the shape and stiffness of lateral fins and control parameters (neutral point, amplitude and frequency of oscillations). Tests were carried out with symmetrical lateral fins which fore part was made of stiff polyethylene. Additionally 3 mm thick elastic rubber endings was added to the lateral fins and tests were repeated. The area of the flexible part longitudinal cross-section of one fin is 4010 mm^2, while the area of rigid part longitudinal cross-section is approximately 3960 mm^2. Both lateral fins are driven from the same servomotor. Taking into account limitations of lateral fins servomotor, the control parameters was also limited. When the lateral fins amplitude of oscillation is from 2.5 deg to 20 deg then the frequency of oscilation does not exceed 6 Hz. When the amplitude is less than 10 deg then the frequency could be increased to 9.6 Hz.

The third mode of CyberFish's locomotion is by means of undulation of its tail while the lateral fins does not oscillate. In this case, the tail undulates accordingly to traveling wave which is typical for carangiform type fish. More detailed description of realization of tail movement with short mathematical description can be found in [5]. The only change is that in this work authors introduced a coefficient which associate six parameters of tails motion (amplitudes and phase shifts of deflection of each segment). This coefficient (namely R coefficient) is the ratio of the length of a CyberFish's tail to the wavelength of traveling wave to which the tail is fitted. Figure 3 presents schematically fitting the simplified tail into traveling wave for different R values.

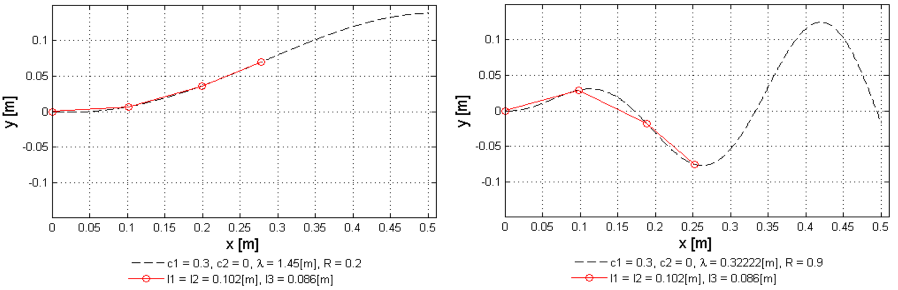

Fig. 3. Fitting CyberFish's tail into traveling wave with different *R* coefficient

Thrust measurements in this case was done for tail frequency changing from 0.2 Hz to 1.6 Hz (0.2 Hz step) and for *R* coefficient from 0.1 to 0.9 keeping in mind tail servomotors limitations.

2.3 Results and Conclusion

Vehicles thrust measurements while CyberFish was in motion using lateral fins movement only was done in two ranges of change of control parameters. In the first range the frequency of oscillations was from 1.2 Hz to 6 Hz while amplitude of oscillation was form 2.5 deg to 20 deg. In the second range, the frequency was from 1.2 Hz to 9.6 Hz but the amplitude was limited and was from 2.5 deg to 10 deg. Frequency change in both cases was with the step of 0.2 Hz and amplitude change was with the step of 2.5 Hz. The tests was done for lateral fins with and without rubber endings. Thrust was measured during vehicle's 18 s long steady state motion then the measurements were averaged. In the figure 4 there are surface plots of measured forces.

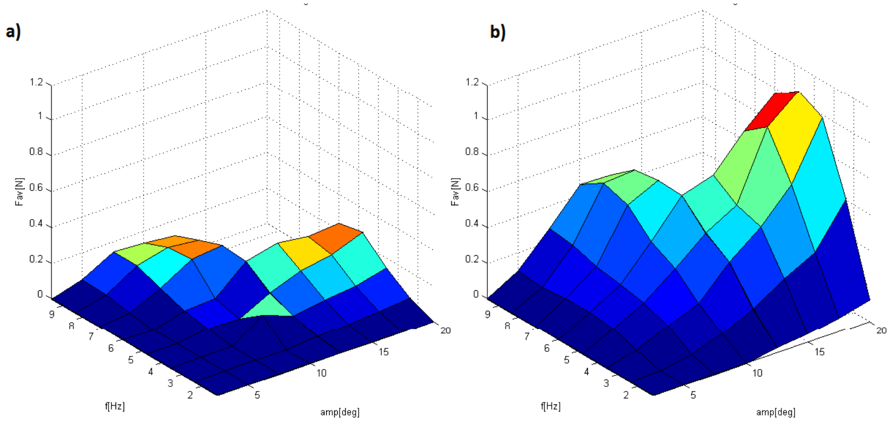

Fig. 4. Surface plots of vehicles thrust, a) without lateral fins rubber endings, b) with lateral fins rubber endings

The maximum force Fav = 1.063 N achieved for f = 4.8 Hz and A = 20 deg. Both the frequency and amplitude increase gives the robot's thrust increase but when lateral fins are equipped with rubber endings the thrust increase is more rapid. The average thrust increase for lateral fins with rubber endings is by 62% while the maximum force is three times higher than with lateral fins without rubber endings. It is worth notice that achieving given vehicle's thrust using low amplitude and high frequency of lateral fins is more desirable than with low frequency and high amplitude. It is because in the first case the heave of the robot is lower. Lo heave of underwater unmanned vehicle is important to maintain good quality of data registered by onboard devices (IMU, sonar, video camera etc.). It also can be seen in the figure 4 b) that there is the peak on the surface (for A = 20 deg, f = 4.8 Hz). After that point further increase of the frequency does not give the increase on the thrust. It is expected that the thrust in high amplitude and high frequency of lateral fins will even decrease due to increasing water drag.

The next part of the experiment involved measurements of the vehicle's thrust while the robot was in motion using its tail only. In this case the tail undulation frequency was changing from 0.2 Hz to 1.6 Hz and R coefficient was changing from 0.1 to 0.9. Furthermore the test was repeated three times: without mounted tail fin, with stiff 1mm thick acrylic tail fin and with elastic 3 mm thick rubber tail fin of the same side area. The tail fin area equals 18670 mm^2 and its shape is homocercal, typical for carangiform type fish. Thrust was measured during vehicle's 12 s long steady state motion then the measurements were averaged. Measured thrust for selected motion parameters and elastic tail fin was shown in the figure 5. It can be seen that depending on control parameters the character of thrust is different. Observed force is characterized by different standard deviation with different control parameters. Standard deviations where the lowest with no tail fin and does not exceed 0.3 N while the biggest standard deviations was noticed for elastic tail fin driven by tail undulation with low frequency and high *R* coefficient.

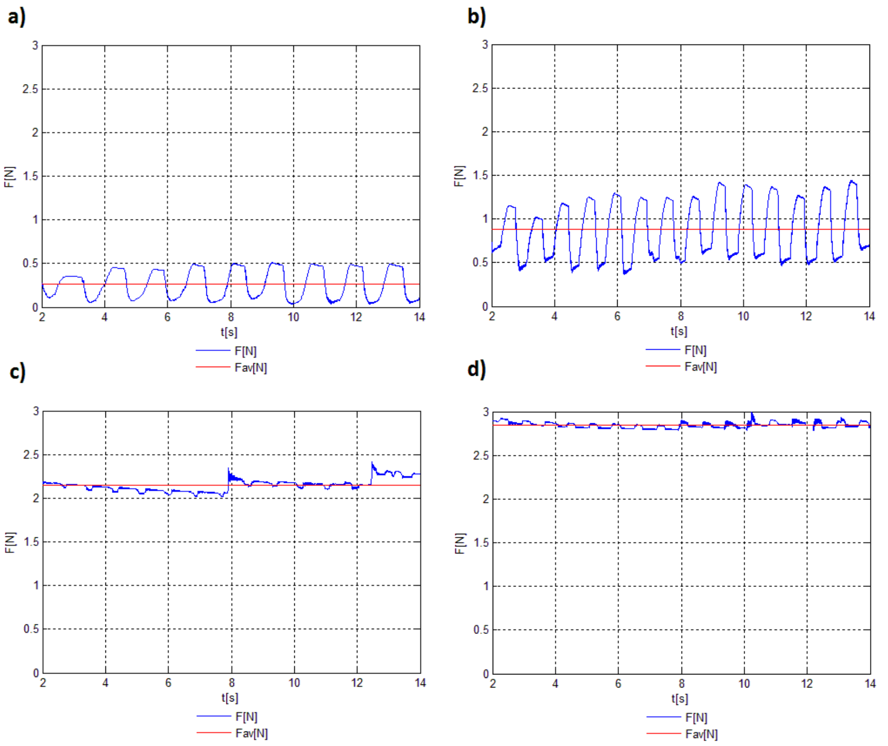

Fig. 5. Selected results of thrust measurements for tail with elastic fin and different control parameters, a) f=0.8 Hz, R=0.3, b) f=1.2 Hz, R=0.4, c) f=1.2 Hz, R=0.9, d) f=1.4 Hz, R=0.9

Figures 6 presents surface plots of the CyberFish's thrust with different tails. The average thrust increase with the increase of frequency of undulations and *R* coefficient as it was noticed with lateral fins. When the tail fin is removed the total thrust of the vehicle is rather low and does not exceed 0.9 N (Fig. 6 a). Maximal force in this case is Fav = 0.8724 N (for f = 1.6 Hz, R = 0.7). When the tail fin is attached to the last segment of the vehicle's tail then the thrust of the robot significantly increases with increasing frequency and R coefficient. It can be noticed that elastic fin gives greater thrust boost at the same control parameters than the stiff one. Maximal registered average thrust was for rubber tail fin driven at f = 1.4 Hz and R = 0.9 and was equal to 2.848 N while the maximum thrust for stiff acrylic fin is only 1.937 N (for f = 1.2 Hz, R = 0.6).

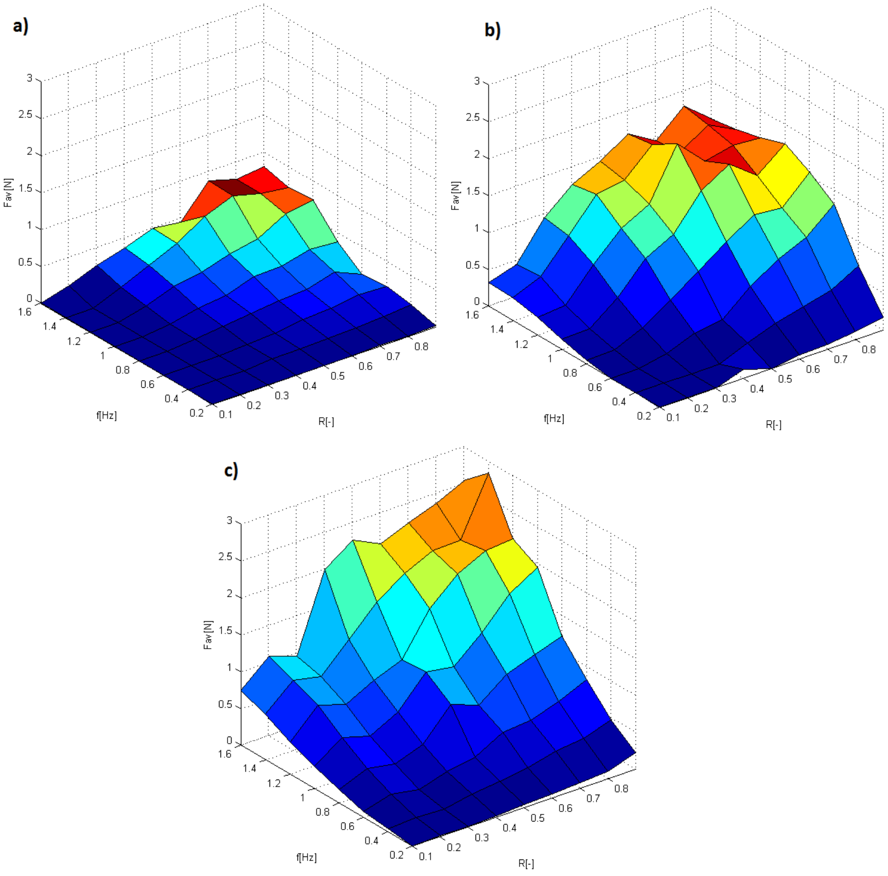

Fig. 6. Surface plots of vehicles thrust, a) tail without a fin, b) tail with stiff fin, c) tail with elastic fin

3 Summary and Future Work

Based on the conducted experiments it can be concluded that the maximum thrust is generated by undulating tail equipped with elastic tail fin rather than stiff one. The highest registered average thrust was in this case almost 3 N. The frequency and introduced *R* coefficient increase also increases thrust but in some ranges causes grater standard deviations of the vehicles thrust. There is the possibility to use lateral fins oscillations for generating vehicle's thrust and using the tail as a big rudder. In this case the average thrust is almost three times lower than the one generated by the tail. Also frequencies and amplitudes have to be much higher than the tails but this type of motion significantly reduces undesirable sway of the vehicle. Greater sway while the robot is driven by the tail is caused by sifting center of gravity of the construction in respect to center of buoyancy. Lateral fins oscillations has another advantage. The thrust can be generated in any direction of vertical plane while the tail generates thrust in limited directions of horizontal plane. This could be useful to increase vehicle's depth control dynamic or even generate reverse thrust when needed.

In the nearest future authors plan to carefully examine dependencies between tail fin and maximum thrust of BUV. Furthermore the optimal parameters of the tail fin are going to be studied and its influence on the robot's energetic efficiency. The appropriate experiment plan will be chosen and object function will be determined. The next step will be to optimize the function using either genetic algorithms or gradient methods [9].

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